Review: Giuseppe Parrella

Comments to the paper:

Characterization of Ice Features in the Southwest Greenland Ablation Zone Using Multi-Modal SAR Data

By S.P. Schlenk, G. Fischer, M. Pardini and I. Hajnsek

The paper presents an investigation based on airborne multi-frequency, polarimetric, interferometric and tomographic SAR data to characterize ice features detected in the ablation zone of the Greenland Ice Sheet. Additional data and results from other studies are used to support the analysis, including ALOS-2 data, P-band sounder measurements, Sentinel-2 optical data, lidar derived topographic data from NASA's IceBridge initiative and in-situ data of ice temperature.

The work focuses on radar-bright and radar-dark features which are more evident with increasing wavelength (i.e at L- and P-band), suggesting a link with subsurface features (weathering crust) and dynamics occurring at the study area.

Dear Dr. Parella,

Thank you for your valuable feedback! Since you have great insight into the dataset, test site, and methods, your input is very much appreciated by us. We truly value your thorough assessment of our manuscript and your insightful comments, which have been helping us to enhance the paper. We have addressed your suggestions and have detailed the corresponding changes in response to each specific comment below.

General comments:

The paper has a clear structure and is easy to read. The analysis is presented in a clear way with an approach that tries to link the different aspects (polarimetry, interferometry, tomography) coherently.

There is potential to get additional insights by expanding the analysis to investigate for instance the dependency of PolSAR and InSAR signatures of the bright and dark features on the imaging geometry. In addition, the use of C-band data would also provide another piece of useful information.

The analysis is supported by a modelling effort which is able to explain the behavior of the PolInSAR coherence at L- and P-band, even though some assumptions, like the presence of specific layers not detectable in the sounder data and in the tomograms, are difficult to justify from a physical point of view.

Overall, the study presents new interesting elements for the interpretation of SAR data of land ice. The interpretation of the shallow subsurface scattering component with the presence of a weathering crust looks reasonable and it is supported by other studies. From a SAR modelling perspective, it suggests a possible source of scattering (to my knowledge) not yet considered in literature, which adds to the previously proposed sastrugi, oriented crevasse fields, volume scattering from air inclusions embedded into ice layers and icy inclusions embedded into firn.

Specific comments:

Eq. 7:
Except the volumetric decorrelation, the other terms contributing to the InSAR coherence are not introduced/defined in the text.

Thank you for pointing out that the other terms contributing to the InSAR coherence in Eq. 7 are not explicitly introduced or defined.
The volume decorrelation is the primary focus and the most significant decorrelation source for our analysis in this paper. However, we understand that readers might benefit from additional context on the other terms. Therefore, we will add an additional citation directly after introducing these terms, directing interested readers to a relevant source for their definitions and further explanation.

Line 180:
I suggest substituting the term 'subsurface ice elements' with 'subsurface scatterers' or 'subsurface scattering sources'.

Good idea! We'll replace the term.

Section 4.1
Here the authors start with the analysis of the PolSAR data which include X-, L- and P-band. As shown in Parrella et al. 2021 (JSTARS), this dataset includes also C-band acquisitions. It would be interesting to see also this data to have a more complete understanding of how the investigated radar-dark/bright features behave with frequency. InSAR and TomoSAR data should be available at C-band as well. Did the authors look at them?

Thank you for raising the point about including C-band data, especially given its relevance in Parrella et al. (2021) and for satellite missions like Sentinel-1 and RadarSAT.
We did indeed analyze C-band data during our study. However, given the already considerable length of the paper and our desire to maintain focus, we made the decision to concentrate on X-band for surface analysis and L-band and P-band for subsurface analysis. We felt these chosen bands most effectively demonstrate the range of penetration and sensitivity to their respective scattering components (surface and subsurface features) that are central to our paper's narrative. While C-band is generally also interesting, it represents an intermediate case between X- and L-band in our analyses. Thus, we believe the current selection provides a comprehensive understanding within the scope of this manuscript.

Line 238:
I believe the authors here refer to Table 1 (instead of Table 2) when discussing about spatial resolution of P- and L-band data.

Thank you for pointing that out!

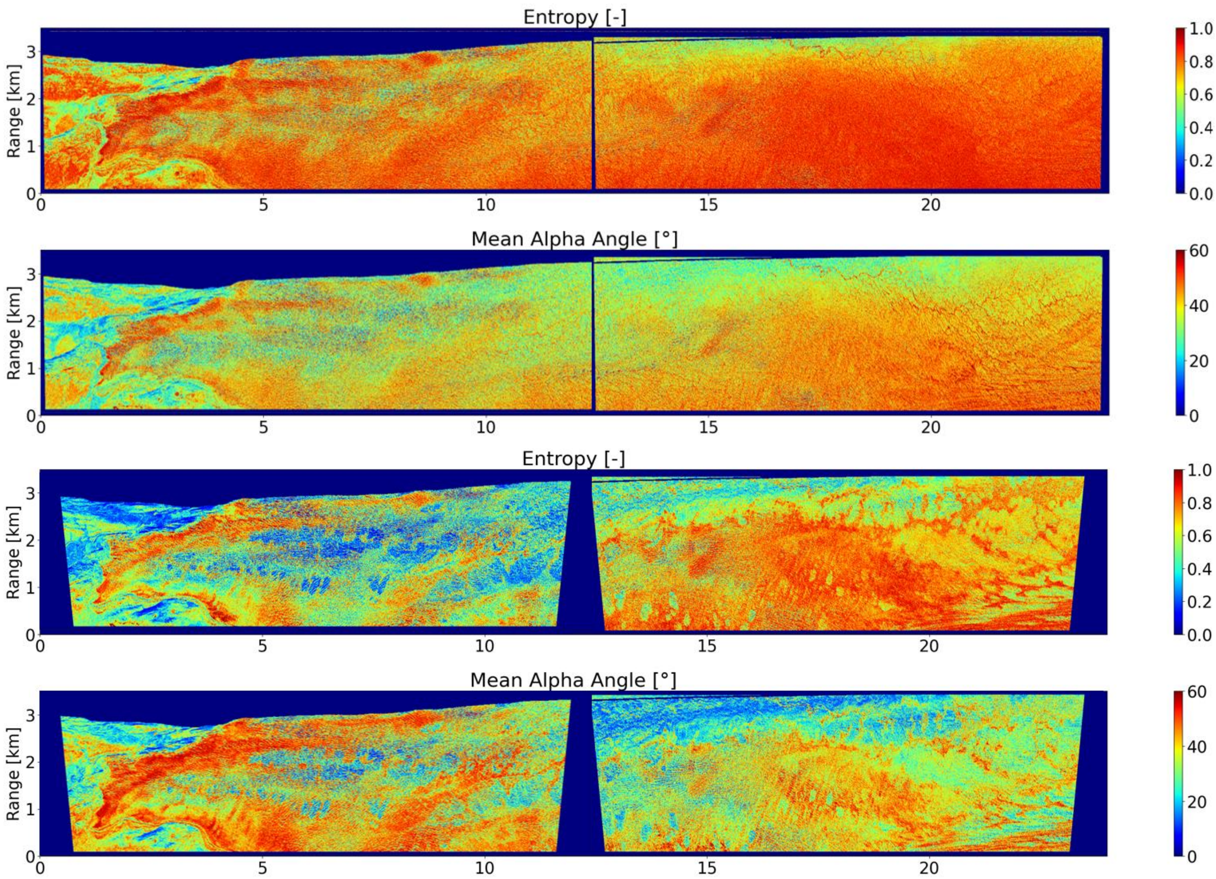
Table 4:
Here the authors report a summary of the value found with the polarimetric analysis at different frequencies.

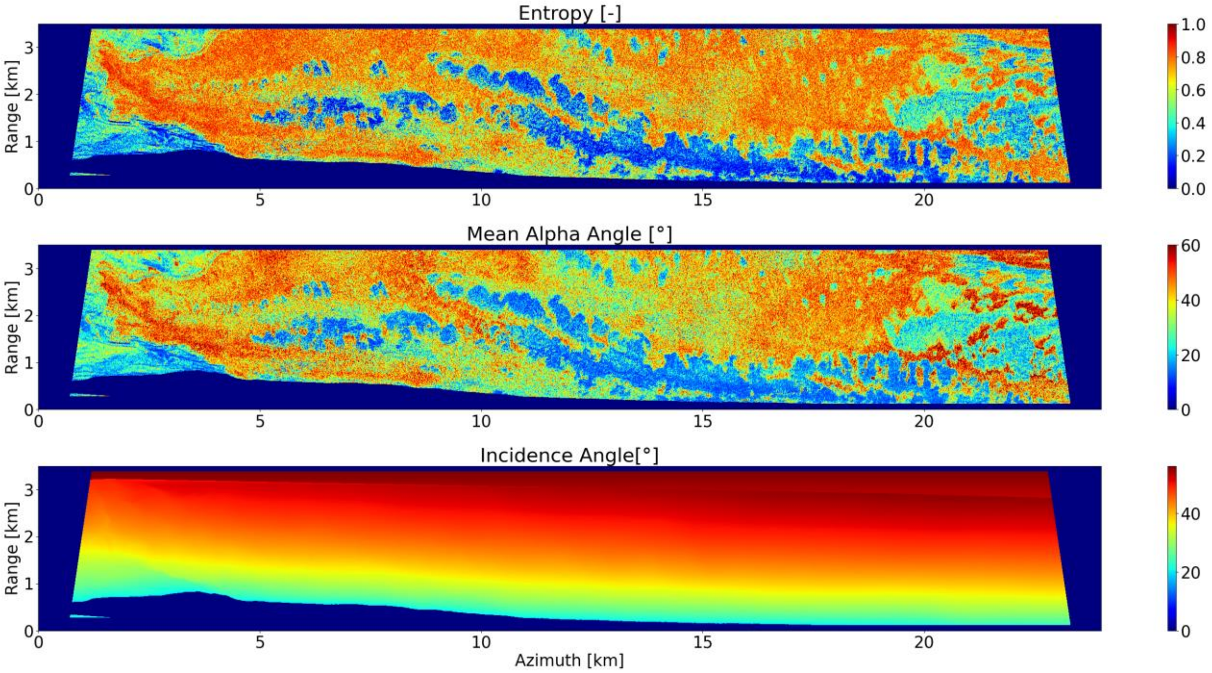
My first point is that polarimetric signatures (including H and alpha angle) are typically influenced by the variation of incidence angle along the range direction. As both dark and bright features seem to be spread along the entire range direction in the SAR images, did the author assess whether the interval of observed H and alpha values is related to variation of incidence angle? Or are those values randomly occurring at different incidence angles? In general, it would be interesting to carry out an analysis of the polarimetric signatures with respect to the incidence angle for both bright and dark features. This might provide additional insights about the type of scattering mechanisms occurring in the two feature types, and support further the results of the InSAR and TomoSAR analysis.

Thank you for this insightful point regarding the influence of incidence angle on polarimetric signatures, specifically Entropy (H) and Mean Alpha Angle (α). You are absolutely correct that these parameters are typically affected by incidence angle variations.

Our findings show a small systematic variation of both H and α with the incidence angle across the range. Here, we observe lower H and α at steeper incidence angles (near range), transitioning to slightly higher values as the incidence angle increases (towards far range). However, as can be seen in the provided plot, visually, Entropy and Alpha Angle stay relatively stable across the variation in incidence angles.

This indicates that while a systematic trend exists, the primary polarimetric characteristics used to distinguish the radar-dark and radar-bright features show smaller incidence angle variations than the general spatial variations (e.g. comparing different dark features). Therefore, we prefer to not include a dedicated analysis over incidence angle. This stability further strengthens the robustness of our interpretations regarding the dominant scattering mechanisms (see P band plots below).





My second point concerns the values observed at X-band for both H and alpha. At shorter wavelengths, I would expect overall higher values w.r.t. L- and P-band. I am a bit surprised to see that for radar-bright features, the lowest value of H and alpha is lower at X-band (0.2 and 0 degrees) than L- (0.5 and 20 deg) and P-band (0.6 and 30 degrees). Interestingly, the figures obtained for the radar-dark features are much more in line with the expected behavior. Do the authors have an interpretation of this phenomenon?

Thank you for this observation regarding the unexpected X-band H and Alpha values for radar-bright features. We agree this needs careful consideration.
We acknowledge that the initial parameters were derived from a sample area, which may not have been fully representative. To address this, we are re-evaluating these parameters using the entire test site, and will include the mean and standard deviation for H and Alpha in the revised manuscript.

Table 5:
Also, here, it would be interesting to know for which incidence angle are the estimated phase center height range representative, and if the authors observed any trend with the incidence angle.

Thank you for this question regarding the incidence angle for the estimated phase center height range in Table 5, and for asking about any observed trends. The range was indeed chosen for a sample area with an incidence angle between 30-40°.
Regarding the trend, our observations align with the general principle that there is less effective penetration with a higher incidence angle. This is because at higher incidence angles, the radar signal travels a longer path through the ice column to reach a given vertical depth, leading to increased attenuation due to both absorption and volume scattering. This effectively limits the vertical penetration capability of the radar. However, the relative difference in penetration between radar-bright and radar-dark stay the same across incidence angle, which is the important message from Table 5.

Line 258-261:
I think that the limited penetration over the radar-dark features could also be related to the lack of effective scatterers deeper into the ice and not necessarily to a real shallow penetration (related to absorption). This is maybe an option to consider here.

Thank you for raising the excellent point that limited penetration over radar-dark features could stem from a lack of effective scatterers deeper in the ice. This is a very valuable alternative to consider. However, our observations lead us to favor the attenuation hypothesis:

- Detection of Subsurface Scatterers Post-Filtering: After applying our matrix filter for surface cancellation, we are able to detect scatterers below these radar-dark features. This indicates that scatterers are indeed present; they were simply masked by the overwhelming signal attenuation closer to the surface.
- Consistency Across Multiple Geometries: It is highly unlikely that there would be a genuine absence of scatterers given our diverse acquisition geometries. We observe this shallow penetration consistently from side-looking SAR in two different headings and from nadir-looking Sounder data. The uniformity of this observation across multiple perspectives strongly suggests a widespread attenuating medium, rather than a spatially variable lack of scatterers.

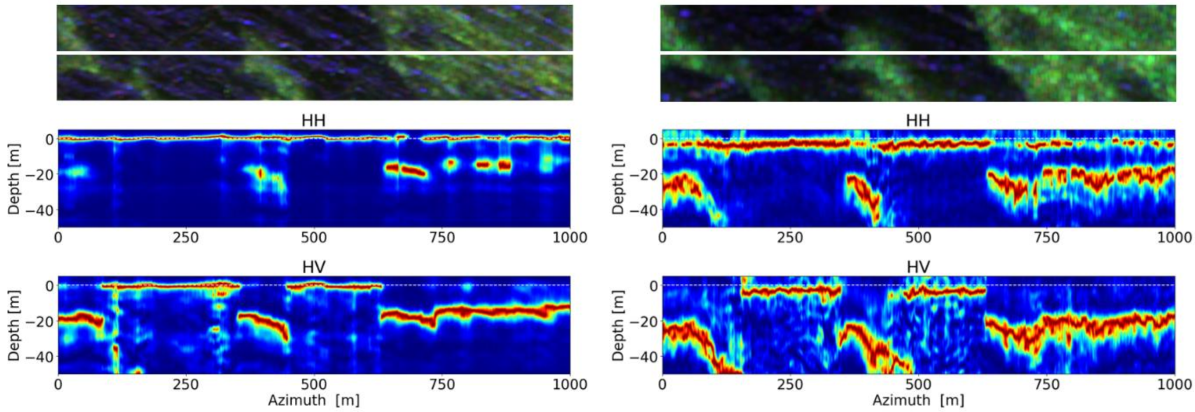
Therefore, while we appreciate considering the alternative, our data robustly support the interpretation that attenuation due to liquid water in the weathering crust is the primary cause of the limited penetration.

Section 4.2.2, Line 284
Please replace 'albedo' with 'snow albedo'

Sure, we'll replace "albedo" with "snow albedo".

Section 4.3.1
It is clear that the authors focus on P-band for the tomographic analysis since this provides an 'enhanced' sensitivity to subsurface scattering and deeper penetration. Anyway, it would be interesting to show and discuss also L-band tomograms and consistent with Section 4.4, where the InSAR modelling addresses both P and L-band measurements.

Thank you for this insightful suggestion. We entirely agree that incorporating L-band tomograms would provide a more complete picture and align well with our multi-frequency InSAR modeling presented in Section 4.4. Therefore, we propose to include an L-band HV tomogram over the same transect as our P-band analysis within the main paper. This will allow for a direct and valuable comparison of the subsurface features at different frequencies.
We have also prepared a direct comparison between L- (left side) and P-band (right side) data over a smaller, representative sample area of 1km in azimuth in both HH and HV polarizations. This figure includes Pauli RGB representations on top with a white transect line indicating the tomogram locations. However, the description and interpretation of this plot is very similar to what is already presented in Section 4.3.1. Therefore, to avoid redundancy and maintain the focus and conciseness of the main manuscript, we propose not to include this plot in the paper itself**.**



Line 376-378

'The general drop of coherence with increasing…. is typical for two scattering components with a certain vertical distance.' Please add a reference.

Yes, certainly, thank you. We will add the reference of Cloude, S. R., & Papathanassiou, K. P. (2003) for clarification.

Figure 8 and 9

I miss here a brief discussion about the values of surface-to-volume ratio obtained to fit the data. Are they reasonable/explainable across polarizations (HH vs HV) and frequencies (L vs P)? The information reported in the appendix is explaining in more details the modelling approach and the obtained results, but it is not discussing them. Please, also provide bigger images.

Thank you for noting the absence of a discussion on the surface-to-volume ratio values for Figures 8 and 9. We agree that a brief discussion of these values is important for a comprehensive understanding; which will be added in Section 4.4. Overall, our modeling approach successfully fits both radar-dark and radar-bright features using the same structural model across all tested polarizations and frequencies for each feature type with the main difference being the different surface-to-volume ratios (as detailed in Tables A1 and A2).

Polarization (HH vs. HV):

- It is generally expected that HH polarization exhibits a higher surface, while HV polarization is more indicative of volume/ subsurface scattering.
- For the radar-bright features, the modeled curves show only slight changes between HH and HV, indicating a consistent scattering behavior with HH having a somewhat higher surface contribution.
- For the radar-dark features, however, the ratio difference between HH and HV is significantly more pronounced. HH polarization shows predominantly surface scattering, whereas HV polarization clearly exhibits a strong volume decorrelation over kz_vol. This results in distinctly different curve shapes between HH and HV for these features.

Frequency (L vs. P):

- Consistent with physical expectations, lower frequencies (P-band) typically penetrate deeper into the medium and are less sensitive to surface roughness, leading to a relatively reduced surface scattering component compared to volume scattering.
- For both radar-bright and radar-dark features, the overall surface-to-volume ratios for L-band are generally higher than for P-band. This trend aligns with the expectation that P-band's longer wavelength interacts more significantly with subsurface volume elements.

Section 5.1 and 5.2

In my opinion, these 2 paragraphs could be removed since they mostly summarize the findings of the analysis carried out in the previous sections.

These two paragraphs indeed summarize the key findings from Section 4. We believe their inclusion is beneficial, particularly for readers who may not be intimately familiar with all the detailed analyses presented in the preceding subsections. This direct summary serves as a bridge, before we move into the discussion, thereby facilitating a clearer understanding of our interpretation and conclusion.

Figures

Please expand Figures 1, 3, 5 to full page width and with better resolution. In some cases, it is difficult to observe the features and patterns discussed in the text (e.g. in Fig. 5).

Yes, thank you for pointing that out. We agree that improving the visibility of the figures is crucial. We will expand Figures 1, 3, and 5 to full page width and ensure they have better resolution, making it easier to observe the features and patterns discussed in the text.